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HIGH-TEMPERATURE ELECTRONIC COMPONENTS AND CIRCUIT DESIGNS*

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ABSTRACT

Downhole logging instruments for geothermal application must have electronic circuits capable of operating from room temperature to 250°C. Previous research was centered on low voltage/low current hybrid microcircuits. However, a nondestructive evaluation (NDE) instrument for geothermal wells requires a circuit that can be operated at high voltage and high current in order to provide high-power output. In designing such a circuit, Sandia Laboratories is developing a high-power, high-speed, cold-cathode switching tube to be used as a substitute for SCRs or thyratrons. The possibility of using low-leakage JFETs beyond their rated temperature in a circuit design will be discussed. Commercial high-temperature components will be reviewed.

INTRODUCTION

Downhole logging instruments are needed to estimate the geothermal reservoir potential and to evaluate the well condition. Logging instruments designed for oil and gas wells are limited by their temperature capabilities (≤175°C), mainly due to the temperature limitation of the electronic components. Previous studies[1,2] had shown the possibility of designing high-temperature microcircuits for logging instruments. However, a microcircuit usually operates at low voltage and low current. Therefore, it is commonly used in a passive device, namely a device that consists of receiving systems only. Successful and safe operation of a geothermal well also requires instruments that are capable of performing various nondestructive evaluations (NDE) of the casing and cement conditions. A device to perform NDE requires a high-power transmitter system in addition to the passive receiving system. A high-temperature circuit that is operated at high voltage and high current, and that is capable of delivering high power, has never been addressed in the literature. Such a circuit design technique is the subject of this paper.

Sandia Laboratories is currently developing a high-temperature, long-life, high-power, high-speed, cold-cathode switching tube. Some Silicon (semiconductor) Controlled Rectifiers (SCR) can provide high-power, high-speed switching, but most of them cannot withstand a temperature of more than 125°C. Various techniques capable of increasing SCRs' operating temperature by an additional 50°C have been explored. However, this temperature (175°C) is still well below that required in geothermal applications. Thyratrons can withstand high temperature, but they require energy to keep the cathode hot. This feature is not practical in a logging tool because it is difficult to transmit large amounts of energy from the surface to the bottom of a well. The cold-cathode switching tube developed by Sandia conceivably can be used to replace SCRs and thyratrons. Hence, this new tube should have widespread application.

Many junction field effect transistors (JFET) have a higher temperature rating (about 200°C) than most other types of transistors, such as bipolar transistors. For some low-leakage JFETs, it is possible to operate at a temperature beyond the rated temperature. The electrical characteristics of a JFET above its rated temperature is different from that at a lower temperature. However, design of a stable JFET circuit capable of operating at temperatures up to 250°C has been accomplished. In addition to the low voltage type, some JFETs with a breakdown voltage between 125 and 300V have been utilized in this circuit design.

High-temperature applications of commercial electronic components, such as capacitors, inductors, transformers, etc., will be reviewed. In the circuit design, JFETs were used to substitute for diodes. The commercial diodes do not have high-temperature capability. In NDE acoustic techniques, a magnetostrictive transducer may be needed. The material selection and techniques to produce constant acoustic output from room temperature to 250°C are examined.

LONG-LIFE SPRYTRON

For fast electronic switching of high current levels, an SCR is commonly used in transistor circuit designs. Unfortunately, most SCRs are only rated up to 125°C. At higher temperatures, an SCR will conduct automatically, even without a trigger signal. In order to extend the operating temperature, a negative gate voltage of -3V to -6V can be applied to turn the SCR off. Another approach is to remove the anode voltage until the triggering time is reached. Both of these methods can increase the operating temperature of an SCR by an additional 50°C. However, this temperature is still well below the 250°C required for geothermal application.

The thrytron is another candidate device for high-power, high-speed switching. Unfortunately, the thrytron is a hot-cathode tube which requires large amounts of energy to keep the cathode hot. This is not practical in a logging instrument because it is difficult to transmit large amounts of energy from the surface to the bottom of a well.

Cold-cathode vacuum discharge tube[3] developed at Sandia appears to come closest to the characteristics of an SCR and is capable of operating at high temperature. This tube, referred to as a Sprytron, has a fast response time (fraction of μs), short recovery time (μs), and high hold-off strength (kv).

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Sprytrons work as well at 250°C as at ambient temperature because these devices are fabricated with high-temperature materials. In the geothermal temperature range, these materials exhibit no significant material property changes. The tube is vacuum exhausted at 600°C for several hours during its processing to remove unwanted gaseous impurities. The Sprytron was initially designed for limited operations (about 200) and requires a minimum of 200-300 volts anode potential, dependent upon circuit parameters, for a guaranteed arc discharge. Because the high voltage could possibly cause the insulation of a logging cable to break down, it is desirable to operate the tube at about 100 to 150V for at least 200,000 operations. (For a 10 pulse-per-second repetition rate and 60 ft/min logging speed, 200,000 operations are sufficient to log a well up to 20,000 feet deep.) Because of the requirement to achieve a long life, Sandia is investigating design modifications to upgrade the Sprytron tube. Figure 1 shows the cross section of a Sandia Sprytron with its typical elements.

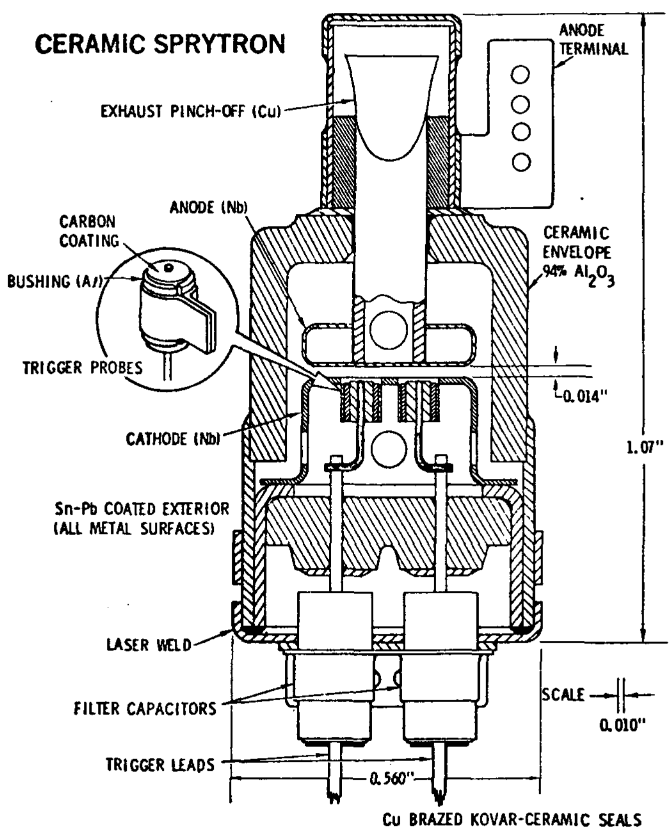


Figure 1. Cross Section of a Sprytron

In order to operate this tube, a fast rising trigger pulse is applied to the probe to cause a spark, initiating plasma across the carbon film between the trigger pin and cathode. This trigger plasma expands into the interelectrode vacuum space and results in a vacuum arc discharge between the main electrodes. The main discharge produces high current which is limited only by the external circuit, with the tube's voltage drop in the 10 to 30 volt range. This high current arc ($\sim 10^8$ amps/cm^2) vaporizes the cathode material and causes erosion of the cathode as tube life progresses. After many discharges, the erosion at the trigger-cathode interface can be so extensive that the trigger pulse may not be able to generate an arc across the spacing between the trigger pin and the eroded cathode. Thus, the tube will no longer function. The discharge can also cause the metal vapor to settle on the surface of the probe, eventually producing a film between the trigger pin and the cathode that may cause a short. However, this failure mechanism may not occur if trigger energy is sufficient to remove the film on succeeding trigger pulses. These deficiencies are the reason that the Sprytron, as currently designed, has limited operating life. In order to improve the lifetime of the tube, various probe configurations, including a larger probe, are being considered.

Appropriate cathode materials could reduce the anode voltage required for a guaranteed arc discharge in the geothermal circuit. Cathode material can also affect the percentage of misfires (inability to trigger) and backfires (hold-off voltage failure at negative anode voltage). In Sandia's special application, the discharge current passes through a magnetostrictive transducer which is inductive in characteristics. The highly inductive transducer will delay the buildup of the arc discharge current (approximately 6 µs to attain 25 amperes). Sometimes this delay may allow the tube to recover from triggering before a complete arc discharge occurs. These shortcomings are being overcome in Sandia's R&D program to upgrade the Sprytron. Recently, a prototype test tube with a large probe has been run successfully for 200,000 switchings.

HIGH-TEMPERATURE TRANSISTORS AND PASSIVE COMPONENTS

In a bipolar transistor, the collector current is controlled by the base current. For most applications, there is a gain in the collector current with respect to the base current. Thus, a small leakage current at the base will result in a large collector current. The energy bandgap of elemental semiconductor materials, such as genmanium and silicon, fall off rapidly as the temperature increases. Although the theoretical operating temperature of the silicon is about 250°C, many bipolar transistors fail above 200°C due to excessive leakage. On the other hand, the drain current in a JFET is controlled by an electric field which is not sensitive to temperature. Sandia's investigation has found that many JFETs can be operated at temperatures up to 300°C, although most of them are only rated up to 200°C.

Since a high-power circuit is the object of this effort, the high-voltage components are emphasized next. Table 1 lists a number of high-voltage JFETs and their leakage current at 250°C. Of the JFETs shown in the table, 2N6449 and 2N6450 have high leakage current that is difficult to compensate for in most applications. On the other hand, JFETs 2N4884 and 2N4886 have the smallest leakage and will be used in Sandia's high-temperature circuit design.

Table 1.
High-Voltage JFET Characteristics

Device	Maximum Ratings at 25°C I_{dss}(mA)	BV_{dss}(V)	BV_{gss}(V)	Leakage Current at 250°C $I_{d,off}$ (μA)
2N4881	2	300	100	40
2N4882	7.5	300	100	35
2N4883	2	200	100	35
2N4884	7.5	200	100	20
2N4885	2	125	75	50
2N4886	7.5	125	75	30
2N5278	25		150	50
2N6449	10		300	300
2N6450	10		200	150

Figure 2 shows the transfer characteristics for a low leakage JFET based on the experimental data. The zero-temperature-coefficient (ZTC) point is quite evident on the graphs.

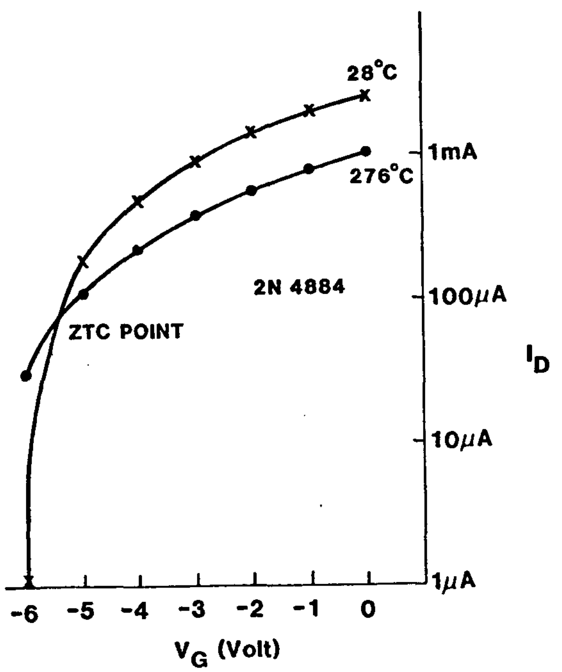


Figure 2. Transfer Characteristics of a 2N4884 (V_{ds} = 150V)

To the right of the ZTC point (less negative gate voltage), drain current falls as the temperature rises. So, any temperature increase due to internal power dissipation will cause a reduction of the drain current. This, in turn, brings about a reduction in the power dissipation and eliminates the possibility of any further increase in internal temperature. On the other hand, temperature increase will increase the drain current to the left of the ZTC point (more negative gate voltage). However, the internal dissipation under such situations is usually well below the dissipation capability of the low-leakage device and, therefore, should not cause any noticeable increase in the transistor's temperature. Therefore, low-leakage JFETs are suitable for high-temperature applications.

As described by Sinclair[4], a simple diode may be the weak link in the chain of vital components in a high-temperature instrumentation system. The carrier diffusion coefficient, carrier diffusion length, the hole concentration in a n-type semiconductor, and, thus, the leakage current of a diode are all temperature dependent. Essentially, for reverse bias, the current increases with temperature in accordance with the factor, $\exp(-E_g/KT)$. Since the energy bandgap, E_g, of a conventional silicon device has low value and decreases as the temperature increases, the leakage current will increase rapidly with temperature. Such a leakage can be reduced by using wide energy bandgap materials, such as the gallium phosphide (GaP) and proper processing techniques. Experimental GaP diodes fabricated and tested at Sandia have shown promising results. It is not known, however, when such a device will become commercially available.

Many JFETs exhibit excellent diode characteristics when the drain and source are connected together into one terminal. As shown in Figure 3, the static forward voltage is less than 1 volt and the reverse breakdown voltage is more than 50V for a 2N4391 connected as a diode.

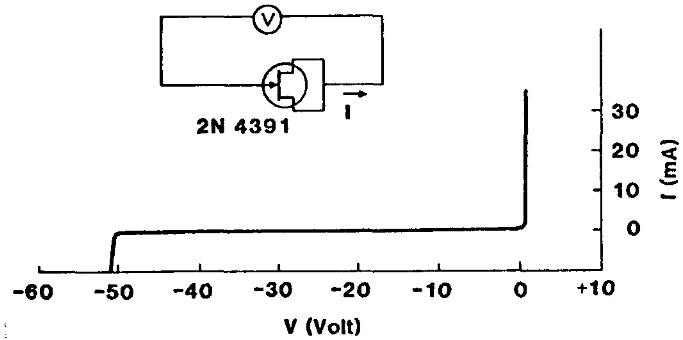
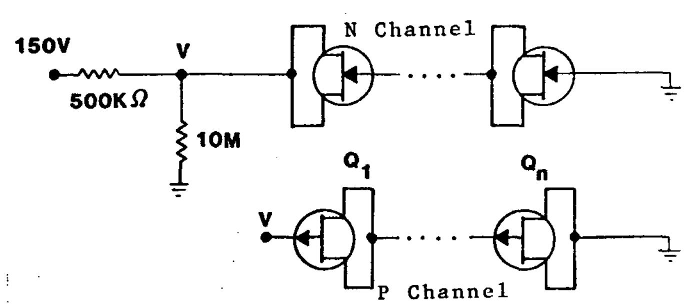


Figure 3. A JFET Used as a Diode

Temperature tests of various JFETs used as diodes show negligible leakage at temperatures up to 250°C for 2N4391, 2N3994, and 2N3823 (Table 2).

Table 2.
Temperature Tests of JFETs Used as Diodes



Q	Channel	30°C	200°C	250°C
2N3823	N	143V	143V	143V
2N3994	P	143V	143V	143V
2N4391	N	143V	143V	143V
2N4881	N	143V	140V	101V
2N4882	N	143V	140V	111V
2N4883	N	143V	140V	110V
2N4884	N	143V	141V	124V
2N4885	N	143V	136V	95V
2N4886	N	143V	140V	115V
2N6449	N	143V	103V	0
2N6450	N	143V	85V	0

High-voltage mica capacitors are capable of continuous operation at 300°C. However, many of these capacitors are not off-the-shelf products and only limited quantities have been produced so far. Therefore, the cost is more expensive and in many cases, the size of the device is large. For example, one commercial 1μf (1kv) mica capacitor is about 1.5 inches in diameter and 7 inches in length. Thus, the dimension of a larger capacitor will not be suitable in a logging instrument. The mica capacitors evaluated today, which ranged from 1μf down to a few pf, show little change in capacitance with temperature up to 250°C.

Many companies can manufacture high temperature transformers and inductors. However, these devices are usually custom designed and sometimes cost thousands of dollars each. If accuracy is not very critical, then they can be made at a much lower price. Many commercial core materials have very high curie temperatures, and their magnetic properties will not change much up to 250°C. High-temperature wires are also available. Both anodized aluminum wire and ceramic-coated copper wire are rated at 500°C, and many magnetic wires are rated for use at temperatures up to 260°C for 1000 hours. If insulation is required, Kapton paper can be used.

Sandia has recently published a sourcebook[5] which summarizes the high-temperature characteristics of a number of commercially available electronic components and materials. This sourcebook provides a good starting point for high-temperature circuit designers.

CIRCUIT DESIGN

Although some electronic components can withstand high temperature, their characteristics may vary with temperature. For example, a JFET at 276°C still behaves as a JFET, but its characteristics are quite different from those at room temperature, as shown in Figure 2. Leakage current is another major problem. Even with the low-leakage devices, such as those given previously in Table 1, the leakage is not negligible at high temperature. Therefore, the voltage/current drift is almost always encountered in a high-temperature circuit design. In an ideal situation, it is desirable to design a circuit such that a drift in one stage of the circuit will be compensated for at the next stage, or a circuit can be designed to operate at the ZTC bias point of the transistor. However, such procedures are usually very elaborate and time consuming. The ZTC point of each transistor is different and should be determined individually. Values of resistors and capacitors for use with transistors should also be accurately calculated and manufactured to these values if the transistor is to be operated at the ZTC point. Althouth this concept has been proven feasible in thick film hybrid technology, the actual production has encountered many problems.[6] In a circuit using discrete components, particularly the high-power circuit, the problems are more difficult to solve.

In this paper, an alternative design for a high-temperature system that is not sensitive to the voltage/current variation in the circuit will be presented. In this special NDE application, a magnetostrictive transducer is selected to generate the acoustic signal. The acoustic signal is related to the transducer's dimension change which is caused by the magnetic flux. Since any ferromagnetic material will saturate at some point in the hysteresis loop as shown in Figure 4, and if the transducer is operated beyond its saturation region, then a constant flux B_s will be produced in every excitation. In turn, this excitation will generate a constant acoustic signal. For example, a 2V permendur core of 0.7 inches ID, 1.2 inches OD, and 0.5 inch height with 20 turns of wire requires about 100 amps to reach a saturation condition. As shown in Table 3, 2V permendur's saturation flux density is almost a constant from room temperature up to 298°C, one main reason for selecting this material. So, if the coil is excited at around 200 amps, and assume that this current would fluctuate between 180 to 220 amps, the flux densities produced after each excitation will still be the same. This equality occurs because these excitation currents are above the minimum current required to cause a complete saturation. Thus, a constant acoustic output will be generated.

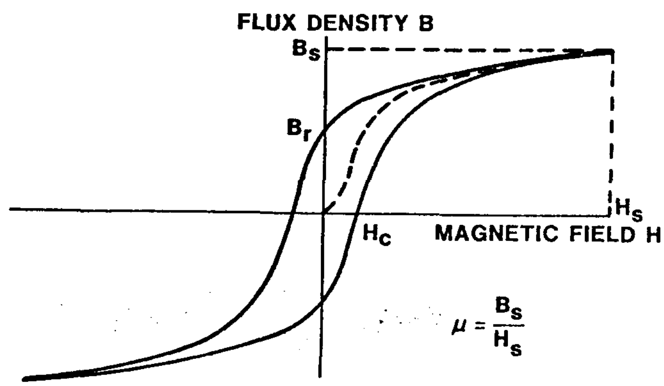


Figure 4. Hysteresis Loop of a Ferromagnetic Material

Table 3.
2V Permendur Thermal Data[7]

T(°C)	B_s(KG)	B_r(KG)	H_c(Oe)	μ	W_h(Erg/cm^3)
23	22.32	14.00	0.300	5580	24050
75	22.30	14.00	0.300	5575	23690
100	22.30	14.00	0.290	5580	22450
150	22.20	15.00	0.285	5560	22810
194	22.18	15.25	0.270	5450	22220
250	--	15.00	0.260	--	19970
298	21.25	15.15	0.255	5310	20150

In Figure 5, a simple circuit is shown that will yield high-excitation current through the magnetostrictive transducer using the Sprytron and high-temperature components discussed earlier.

The over-voltage gap used in Figure 5 breaks down at about 400 volts. Therefore, a high voltage is required at the terminal V_o. The RC values and the breakdown voltage of the gap will determine the repetition rate. Due to the possibility that the insulation of the long logging cable might break down, it is preferable to generate high voltage downhole by using a voltage multiplier as shown in Figure 6.

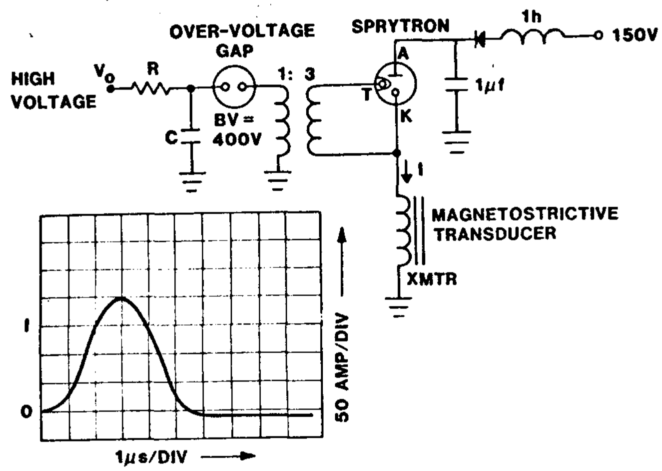


Figure 5. Transducer's Excitation Schematic

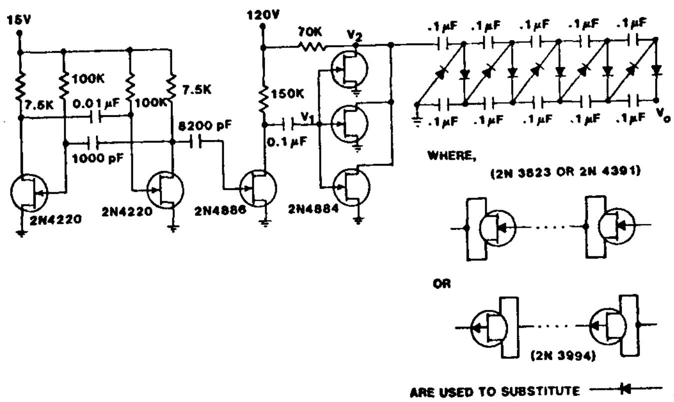


Figure 6. Oscillator and Voltage Multiplier

The oscillator frequency drifts from 6KHz at room temperature to about 10KHz at 250°C as shown in Figure 7. However, the output voltage at the voltage multiplier (V_o in Figure 6) only changes from 537V at room temperature to 470V at 250°C, roughly 12%. This degree of change is relatively small, considering the wide temperature range. In particular, 250°C is well above the rated temperature of the JFETs used. The voltage variation could affect the repetition rate. However, if the triggering time is used as the reference at the receiver, then changes of repetition rate will not influence readings. The voltage variation can be further reduced if the JFETs in the oscillator are operated at their ZTC bias so that the frequency drift in temperature is minimized.

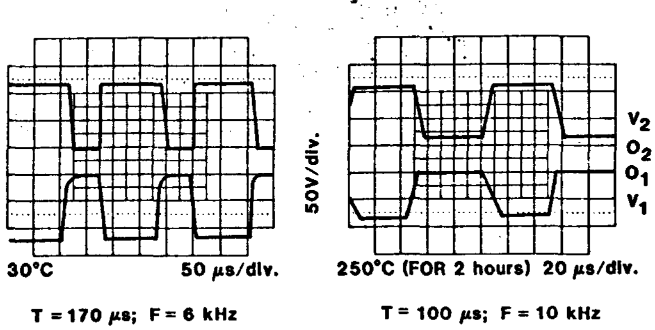


Figure 7. Frequency and Voltage Variations with Temperature

In Figure 6, a low voltage (∿-6V) at V_1 would have been sufficient. However, the leakage current of a JFET from different manufacturers does vary, hence, the value of V_1 could change also. In order to guarantee enough voltage at high temperature to cut off the drain current of the 2N4884 at the next stage, a high-voltage JFET is used to produce large negative gate voltage at V_1.

In conclusion, it is considered feasible to design a high-power circuit for operation at temperatures ranging from room temperature to 250°C, using current technologies. Careful selection of high-temperature components is the key to a successful system which can be designed to operate in such a way that the voltage/current variation at temperature will not affect the transmitter's output and the receiver's reading.

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